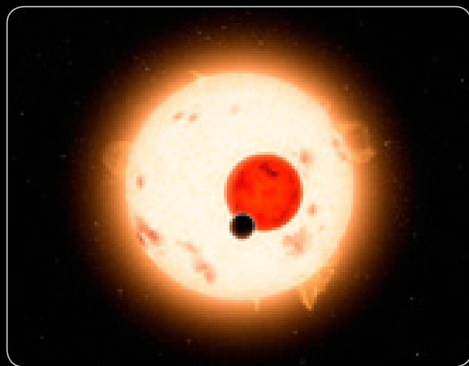
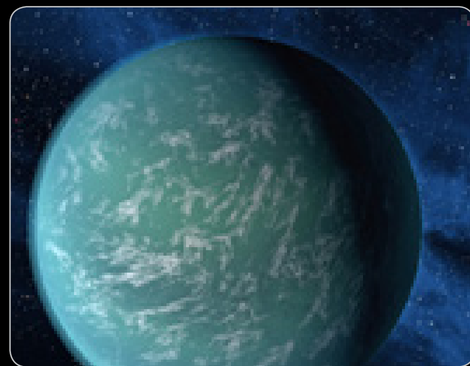
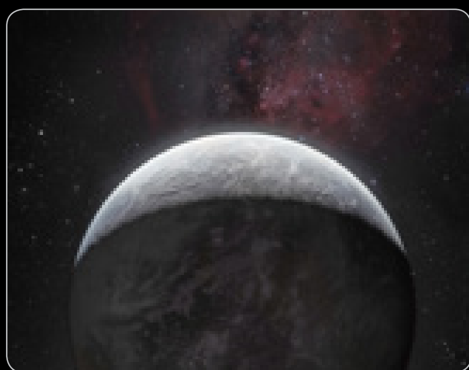
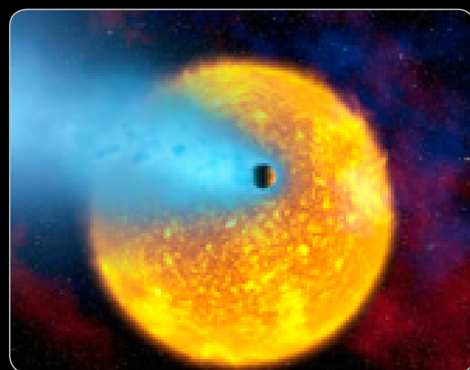
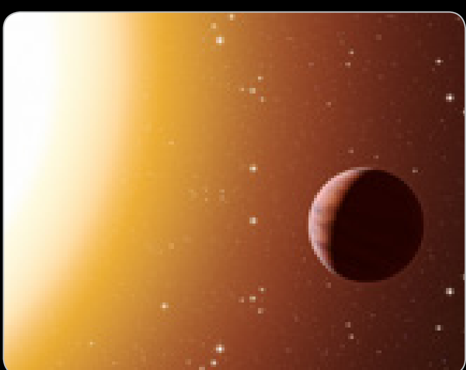
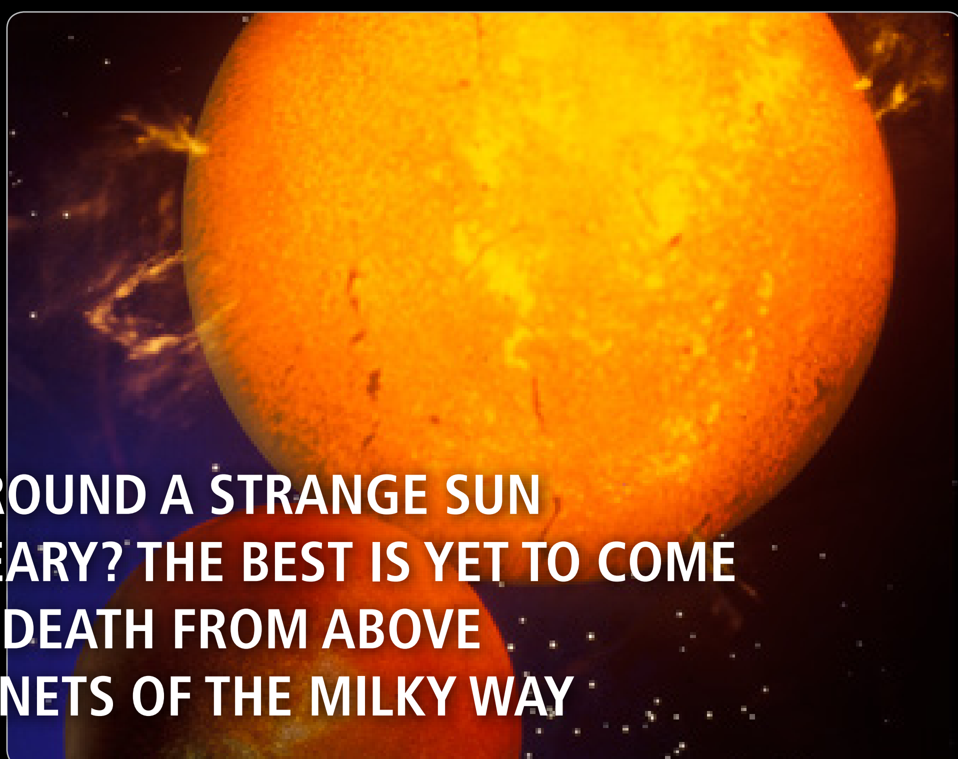
SCIENCE FOR THE CURIOUS
Discover
MAGAZINE

EXOPLANETS

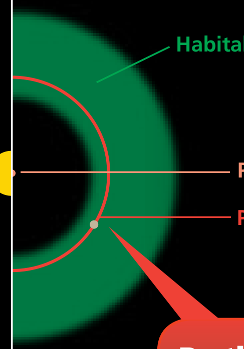


AROUND A STRANGE SUN
WORLD WEARY? THE BEST IS YET TO COME
DEATH FROM ABOVE
PLANETS OF THE MILKY WAY

Around a Strange Sun

Explore the alien landscape of Earth's nearest neighbor.

After decades of failed searches, astronomers from the Pale Red Dot project found a planet around our nearest star, Proxima Centauri. This world, Proxima b, is roughly Earth-sized and nestled in its star's habitable zone — the region where oceans can exist. But that's about where the similarities end. Proxima Centauri is a cool, tiny red dwarf star. To stay warm, Proxima b's orbit is tighter than Mercury's. — ERIC BETZ



Darkness and Light

Proxima b's close-in orbit may mean the planet is tidally locked, with one side stuck in sunlight, the other in eternal night. If so, life's best chance is in the twilight between the two, bathed in a kind of everlasting sunset.

Habitable Zone

To calculate where liquid surface water can exist, astronomers combine a star's heat with the sunlight reaching a planet's surface. But even a Goldilocks-perfect orbit is no guarantee of life. Mars is in our sun's habitable zone and was left barren without an atmosphere.

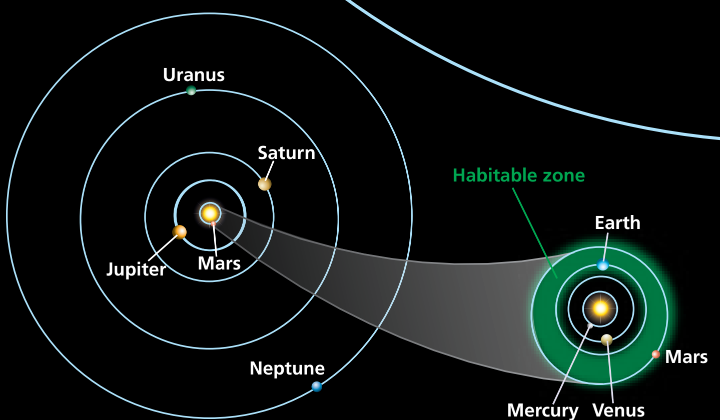
By the Numbers

11.2 The number of Earth days it takes Proxima b to orbit its sun — that's a short year!

1.3 The minimum mass of the newly discovered planet, compared with Earth.

4.6 million Distance (in miles) from Proxima b to Proxima Centauri. Compare that with 93 million miles from Earth to the sun.

SOURCE: NATURE; DOI:10.1038/NATURE19106



Proxima b's radius might be **10%** larger than Earth's, assuming a rocky composition.

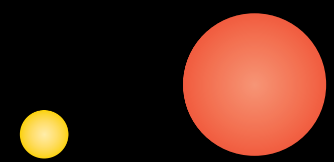
Earth

Proxima b
(artistic representation)

LARGE ORBIT DIAGRAM: ALISON MACKEY/DISCOVER AFTER ESO/M. KORNMESSER/G. COLEMAN. SOLAR SYSTEM DIAGRAM: ROEN KELLY/DISCOVER. EARTH, PROXIMA B, PROXIMA CENTAURI: PHL@UPR ARECIBO/NASA EPIC TEAM. SUNSETS: PHL@UPR ARECIBO. SUN: SDO

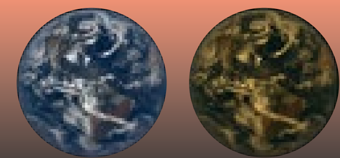
Red Dwarfs Everywhere

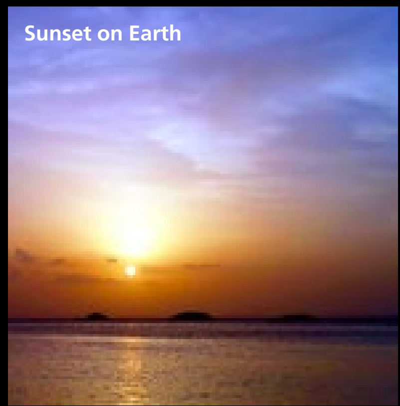
If the Milky Way had just 100 stars — it's more like 100 billion — 75 would be red dwarfs. Finding a roughly Earth-sized world in the habitable zone next door means those other small suns might harbor similar planets.

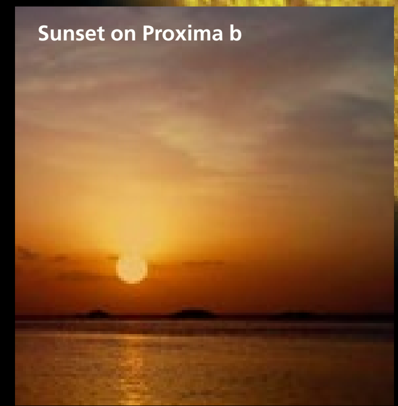


A Drab Planet

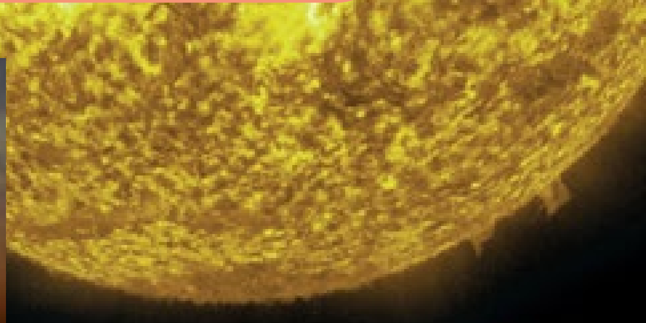
If Earth orbited a red dwarf star, its light would make our pale blue dot take on more of a drab, greenish-yellow tone.







Proxima b hugs tight to its tiny red dwarf star. So sunsets would look redder and darker, with the sun appearing three times larger than our own. Stranger still: If one side of Proxima b forever faces its star, the sun would never set.



Actual size difference

ON THE WEB

Readers respond

Proxima b is the nearest exoplanet we'll ever find. When news hit the web, Discover readers were pumped, to say the least.

"This is as good as it gets, in our own backyard!" —Joanna Leigh

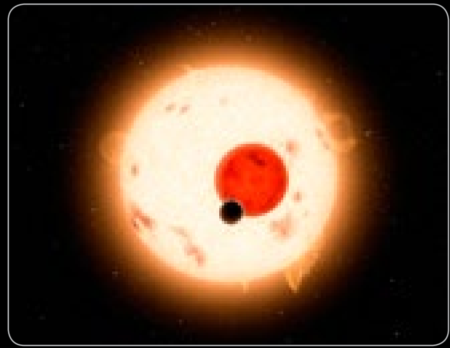
"Although very interesting … I believe it will be uninhabitable. Nice dream, though. We should continue trying to find a habitable planet that parallels our own." —Sharlyn

"Very promising. It would take technology we haven't invented yet, but it is at least theoretically possible that we could send an unmanned probe to Proxima b." —Erik Bosma

"Why go there at all? Just build a giant kick-ass telescope and look at it." —Brian Hurren

"Hopefully there is intelligent life on this new planet. They must have it somewhere." —Michael

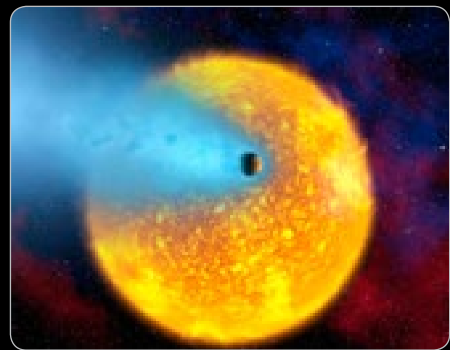
Sending an unmanned probe to Proxima b may happen sooner than you think. Read about it on page 32.

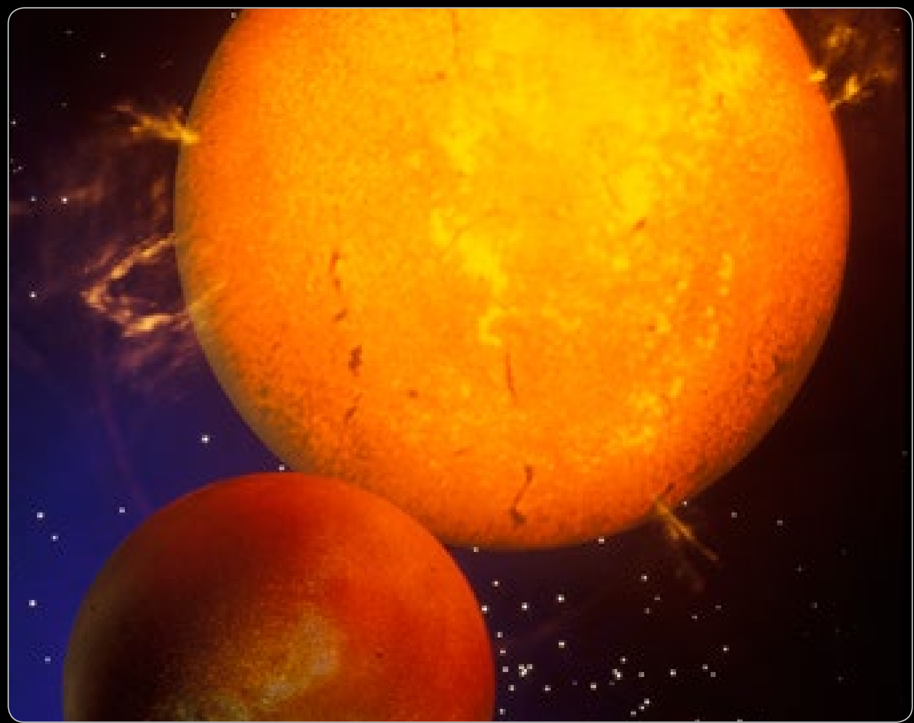




World Weary?
The Best Is Yet to Come

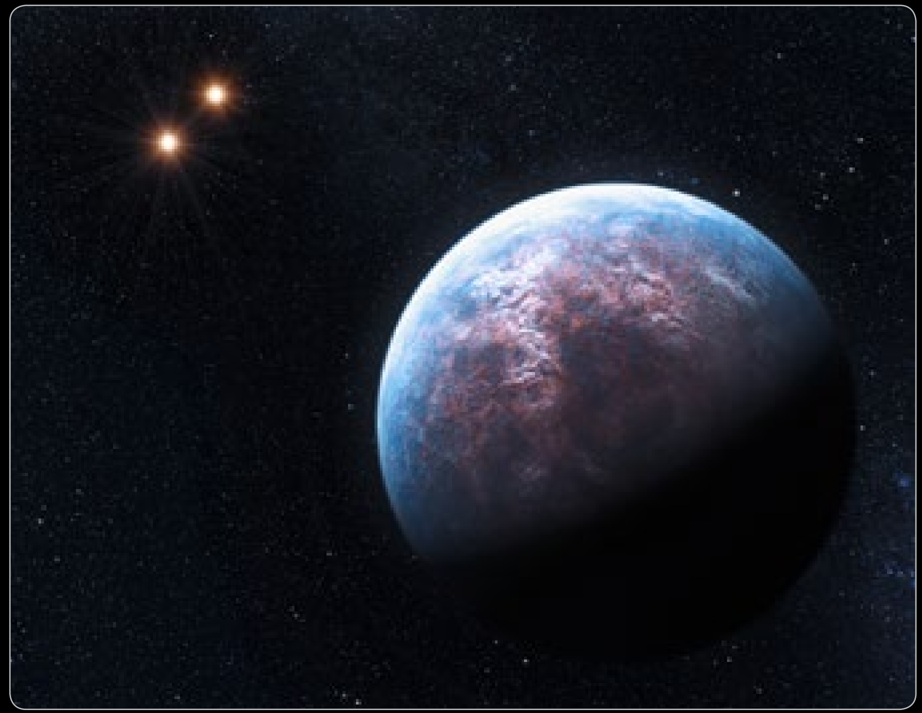
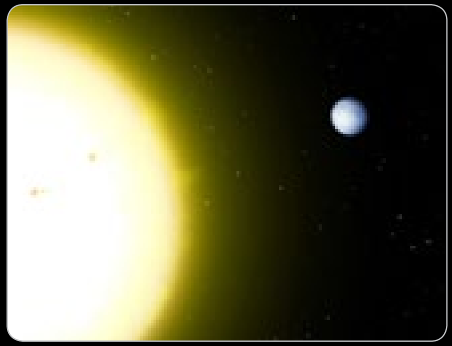
Call it exoplanet fatigue. With discoveries rolling in every day, here's why we should still care about finding new alien planets. BY SARAH SCOLES





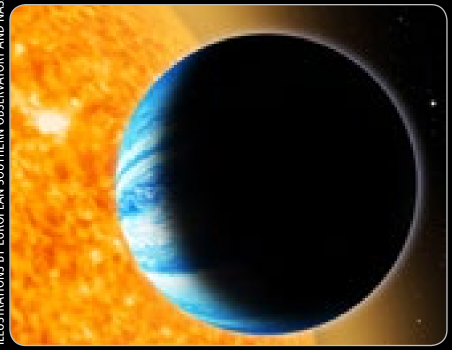



ILLUSTRATIONS BY EUROPEAN SOUTHERN OBSERVATORY, EUROPEAN SPACE AGENCY, AND NASA/JPL-CALTECH. BOTTOM RIGHT BY SETH SHOSTAK





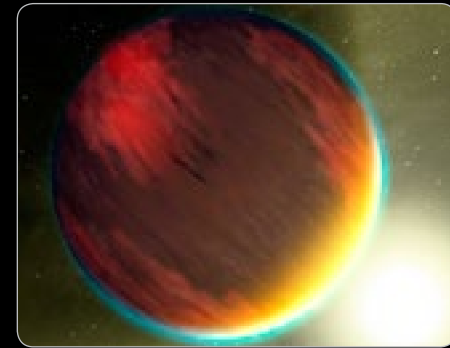


ILLUSTRATIONS BY EUROPEAN SOUTHERN OBSERVATORY AND NASA. BOTTOM LEFT BY HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

Astronomers have been finding exoplanets out in the cosmos for 25 years, and if we've learned anything about all those planets, it's that a lot of different, weird kinds exist. They are big and hot and close to their stars. They are smaller than Earth. They are gassy and Jupiter-y. They are rocky and terrestrial. They are so cold even the most extreme earthly organisms would freeze to death. They are so hot they could melt glass. They rain glass. They are by themselves. They have neighbors. They are far away. They are right next door.





And over the years, astronomers have found more and more planets that are increasingly "like" Earth — at least in terms of their size, their distance from their stars, and potentially their compositions and characters.

On Aug. 24, 2016, astronomers announced a potentially habitable, likely rocky planet orbiting the star nearest us, Proxima Centauri. Certain corners of the internet freaked out, dubbing it an "Earth-like planet" and calling for interstellar travel. Proxima b, as the world is known, is among the smallest known exoplanets, mass-wise, and it's as close to Earth as one can get. But it's not substantially smaller than many others, and it's not guaranteed to be any more Earth-like, either. Proxima b fell from the public consciousness and the front page within weeks, just one more among 3,565 other known exoplanets.

Because big announcements like this happen regularly now, every year or so, it's easy to just say "cool" and move on. Readers are used to seeing news stories about the next-closest-to-Earth-sized planet, the maybe-could-be-Earth's-twin planet, the no-really-this-time-it's-like-super-close-to-maybe-being-like-how-Earth-is planet. And with that escalation, exoplanets have begun to seem very normal, even possibly boring.

Astronomy fans have begun using the term "exoplanet fatigue" to describe the mindset that comes with yet another announcement of otherworldly, and potentially worldly, worlds. When every near-Earth-sized planet gets hype, and thousands of others are announced at a time, it's easy to feel like we should just put planets in the same been-there-done-that category as stars: Discovering more is *just* adding to a pile no one cares about.

But we should resist that urge toward apathy. Exoplanets haven't finished changing our worldview, our universe-view, our view of life itself, scientists say. Their work is just beginning. They hardly know anything. After all, it wasn't that long ago that these worlds were little more than science fiction.

THE REALITY OF EXOPLANETS

For a long time, astronomers thought planets were hard to make, perhaps requiring "two stars to pass close enough to each other to pull out material in a disc," says Jill Tarter, who worked on some of the earliest exoplanet telescope plans and is considered a pioneer in searching for extraterrestrial intelligence. Planets emerged from that two-star-spun disk. But how often do two stars come that close to each other? Not often.

The current standard scientific canon suggests that stars, and planets, form from a shrinking cloud of gas. After the gas collapses into a dense enough clump to start its path toward stardom, its gravity flattens the remaining gas into a disk. Flecks of dust and molecules of gas smack into each other and stick together, giving them more mass, and hence more gravity, which attracts more dust and gas to them. This process snowballs, and eventually the small clumps grow into small planets, big planets, asteroids and comets. But this idea didn't mature until the 1980s, and even then most scientists continued to believe that conditions had to be just right to make planets, which they thought were uncommon.

But people began searching for them anyway, and then the discoveries started to trickle in. In 1992, astronomers Alexander Wolszczan and Dale Frail found two planets around a pulsar, the husk of a star left over after it explodes as a supernova. Three years later, astronomers Michel Mayor and Didier Queloz discovered a planet about half the mass of Jupiter, whirling around a sunlike star in a roughly four-day dance. Planets kept popping up, as people used ground-based telescopes to detect the stretching and shrinking of a star's light waves — the result of the tug of a planet's gravity. Scientists' ideas about the abundance of other worlds began to change; maybe it wasn't so hard to make a planet after all.

But there was an even better way of looking, first detailed in 1971 and revised by Bill Borucki, formerly of the NASA Ames Research Center in Mountain View, Calif., in the mid-1980s. A telescope could stare at a star and wait for it to dim — just a little — when a planet passed in front of it and blocked some of its shine. This is called a transit, and Borucki was convinced that it would work on a large scale. He wanted to build an orbiting telescope that would watch a wide swath of space, and all the stars within, at once. He began proposing it officially in the early 1990s and tried four times until, in 2000 (fifth time's the charm), NASA approved it.

With its launch nine years later, the Kepler space telescope was born. The underlying hope, of course, was biology-based: to find a planet truly like ours, where life could survive, or even thrive. And, along the way, scientists would be thrilled to learn more about planetary dynamics and demographics.

When the first results came back, Kepler mission instrument scientist Doug Caldwell took his first look at the data on a known planet. "It was so clear, and it looked like a fake computer model," he says. "We were amazed. It really worked!"

KEPLER'S CENSUS

Kepler's impressive work has revolutionized the field. It gave us so many planets — and enough rocky, Earth-ish ones — that we now find these once-extraordinary worlds commonplace.

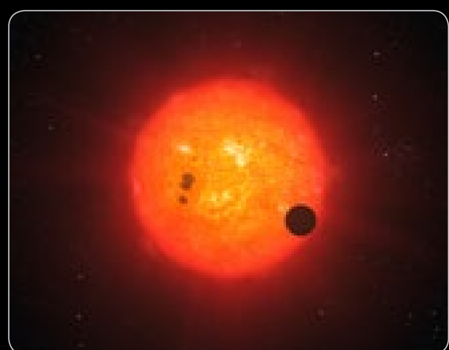
As Kepler stayed in space longer, it gathered enough data to detect smaller planets, farther from their stars. At first, Caldwell's team confirmed planets individually, pointing a ground-based telescope directly at a given star system. But soon, Kepler had amassed entirely too many candidates — the team had to find another way to confirm them.

And that, says Caldwell, caused another shift in the field. Astronomers decided they didn't need to *know* each candidate planet was a true planet: They could just be 99 percent sure. They began confirming the existence of other worlds in batches, using a statistical validation technique that matches transits against models to see how likely it is that they *probably* come from a planet. "If you pick any individual one, it might not be a planet," he says. "Chances are it is, but it might not be. But if you take the whole set of them and you want to try to understand properties of them, you can make very good conclusions based on that because you know that most of those — 99 percent — are really going to be planets."

This idea works partly because planets are so common — so easy to make — that, chances are, the scientists aren't misinterpreting the signals. Astronomers estimate, based on past observations, that the number of Earth-sized planets in our galaxy approximately equals the number of stars, roughly 100 billion.

Suddenly, scientists could do demographic studies on the planets, just like pollsters do with census data. What percentage of people with incomes under $45,000 live in one-person households? What fraction of planets within 100 million miles of their star are more than twice the mass of Earth? That catalyzed another shift in scientists' thinking, from the quest for Earth's twin to the analysis of what its many

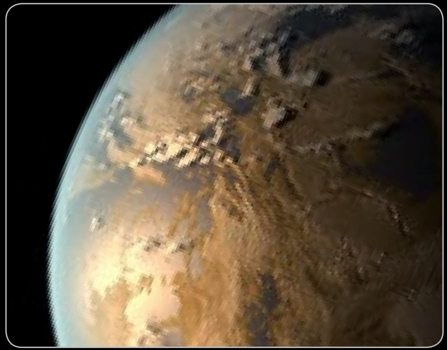

These colorful illustrations capture the stunning variety of known exoplanets.

TOP FROM LEFT: NASA; UNIVERSIDAD DE CHILE; KHENG GUAN TOH/SHUTTERSTOCK; BOTTOM: NASA (3)

NASA (5); BOTTOM ROW CENTER: LEIDEN UNIVERSITY





FROM LEFT: NASA/AMES/SETI INSTITUTE/JPL-CALTECH; NASA/JPL-CALTECH; NASA AMES/JPL-CALTECH/T. PYLE

and varied siblings are like. It went from "we're going to find Earth," says Caldwell, to "we're going to find lots of things that could be like Earth and try to understand how their properties vary around different stars."

Some solar systems mirror our own, with a neat set of planets lined up in a flat plane like a posed portrait, small ones mostly close to the sun and big ones farther out. Others have hot Jupiters, big planets that live very close to their stars; still others have planets in wonky orbits at weird angles to each other. Yet others have mini-Neptunes and super-Earths, varieties that don't show up at all in our own family photo.

Even 25 years after finding the first exoplanets, and thousands of discoveries later, we still don't have an answer to the questions that spurred the Kepler mission in the first place. How did solar systems get to be the way they are? And how often does a livable planet like Earth — really like Earth — come to be?

BUT WAIT, THERE'S MORE

That remaining uncertainty and potential don't always come through in headlines or TV reports, though, which focus more on excitement over the latest find. Take the coverage of Proxima b: Many press releases and breathless news stories splashed the words "habitable" and "Earth-like," adjectives that have also appeared in dozens of discovery articles in the past.

To be clear: Humans currently know of no certainly habitable or even just Earth-like planets. But when scientists and the media throw these terms around, they suggest that astronomers have already found everything they've been looking for in a planet. People think we've *already* found an Earth twin. No wonder they lose interest.

The first problem is that scientists' phrase "in the habitable zone" sometimes gets shortened — by scientists, the press and people's minds — to simply "habitable." Scientists say the former and mean "could host liquid water," but that gets morphed into the latter and, effectively, "could host life."

"Those words have different meanings in English, which is what the public is actually going to read," says Rory Barnes, an astrobiologist at the University of Washington. "'Oh, it's in the habitable zone, ergo it's habitable,' and it makes perfect sense to do that."

On top of that, the habitable zone means different things to different people. Determining the exact boundary — this side of the imaginary line can host liquid water, this side can't — depends on many factors beyond just the hike from the planet to the star. The planet's internal composition and its atmosphere, as well as the star's stability and intensity, all play a role.

To reflect that complexity, Barnes has developed a metric called the habitability index for transiting exoplanets, which comes a little closer to telling whether they'd be habitable, in the true English-dictionary sense of the word. The traditional habitable zone is binary: Yes or no, a planet is in it or it's not. But the habitability index gives the probability that a planet actually has liquid water, after taking into account the surface temperature of the planet. He hopes that scientists can use the index in the future to decide which planets next-generation telescopes should pay most attention to. Those telescopes will be able to tell not if a planet could be Earth-like, but if it actually is another Earth.

If the public knew how close we could be to finding an actually habitable planet — and that we hadn't really found another Earth yet — that'd surely spike their interest.

THE MEYERS-BRIGGS INVENTORY OF PLANETS

"'Earth-like' is probably even more fraught with problems than 'habitable zone,' because what does that mean?" says Caldwell. "To my mind, if something is Earth-like, there's trees, there's water, and [similar] things. That's certainly not what we're talking about because we have no idea."

But it turns out we soon might. The personality details of planets — details beyond their superficial attributes of size, weight and neighborhood — are starting to come into view. Some of the next generation of telescopes plan to zero in on Proxima b, a less-extreme zoom than what's required for other similarly sized planets that live farther away.

The coming studies with next-generation telescopes like the James Webb Space Telescope and the Transiting Exoplanet Survey Satellite aren't just about finding new worlds; they are about exploring them, via their atmospheres.

Scientists are interested in biosignatures, or combinations of molecules indicating the presence of life as it breathes, eats, photosynthesizes or otherwise interacts chemically with its environment. Biological processes like these leave chemical concentrations out of their natural equilibrium, telling scientists that something — or someone — must be altering them. On Earth, for instance, the atmosphere contains oxygen and ozone with relatively little methane, which indicates photosynthesis is happening.

So far, scientists have only been able to see the spectra from a few planets' atmospheres, as they need bigger and better telescopes, with special equipment to block starlight, to really get to know a planet. Maybe we should wait for that before giving in to boredom with exoplanets. After all, a pile of census data doesn't mean humans are boring and mundane because we know so many of them exist in so many forms. It's the individuals that really spark interest, that tell you why the population matters; we should give exoplanets the same chance.

VIVE LA RÉVOLUTION SCIENTIFIQUE

The scientists get it: So far, there's only been so much to get excited about. "Maybe a certain amount of fatigue in the public is natural and fine," says Aki Roberge, an astronomer at the NASA Goddard Space Flight Center in Greenbelt, Md., "as long as when the time comes that we really do discover something crazy-amazing, we're still able to get people to pay attention."

That crazy-amazing thing is an actually Earth-like, actually habitable, perhaps actually inhabited planet. And it's still in the future. Tarter calls the 21st century "the century of biology on Earth — and beyond."

Roberge elaborates on the same idea. "I do believe we're standing on the verge of a scientific revolution," she says. "But it's not in astronomy, per se. It's actually in biology. And the discovery of life on other worlds — of an independent line of life — would be as revolutionary as the realization that the sun was a star or that those moving lights in the sky are planets like the Earth." Or, perhaps, that Earths are as common as stars throughout the cosmos.

It could be in a couple of decades, Roberge says, or 100 years, or more. There's no way to know. But she imagines that just as Newton's laws of gravitation govern how planets interact with each other (and how you interact with the ground), a parallel set of laws governs how life arises or doesn't, and then survives (or doesn't). "Maybe life is rare," she says. "Maybe it isn't. But I think that the habitable conditions that Earth-like life could tolerate — I don't think those are rare."

The only way to know is to keep looking, to keep amassing more planets (and announcing them), to start probing their atmospheres from afar. With tomorrow's telescopes, that revolution will come, and it will be glorious. Now that's something to get excited about. D

***Sarah Scoles** is a science writer in Denver. Her last article for* Discover *was September's cover story, "Target: Earth."*


LEFT: NASA/CHRIS GUNN. RIGHT: NASA/GSFC

Engineers recently assembled all 18 hexagonal components of the primary mirror of the James Webb Space Telescope (left), the successor to Hubble. The Transiting Exoplanet Survey Satellite (TESS, above) will directly search for new exoplanets among more than 200,000 stellar targets. Both next-gen telescopes will help us get to know exoplanets even better, perhaps even detecting the signatures of life — if it exists.

DEATH *from* ABOVE

DO BIG EXTINCTIONS COME LIKE CLOCKWORK — FROM SPACE?

by **SARAH SCOLES**
illustrations by **ROEN KELLY**

From comets to cosmic rays, threats known and unknown lurk as Earth moves around the sun, and our solar system moves through the Milky Way. Growing research suggests some of those threats may cause cyclical mass extinctions.

Back in 1977, geologist Walter Alvarez returned from a scientific expedition to Italy with a peculiar rock sample, liberated from limestone that was once underneath a long-gone ocean. The rock's older, bottom layers were full of fossils. But above them was a layer of clay that had none. That layer captured the aftermath of an event 66 million years ago, when *something* caused a mass extinction, slaying 75 percent of the species on the planet, including *T. rex* and triceratops.

A layer of rock (orange arrows, below) in a sample similar to one retrieved by Walter Alvarez captures the immediate aftermath of a mass extinction.

Luis (left) and son Walter Alvarez in the early 1980s near Gubbio, Italy. Years earlier at the site, Walter collected a rock sample that stored evidence of an extraterrestrial cause for the extinction of 75 percent of life on Earth some 66 million years ago.

When he showed it to his physicist father, Luis Alvarez, both became obsessed with studying this rock, convinced it held the answer to what was, at the time, a huge mystery: What killed the dinosaurs?

Over time, scientists would amend that query to "What killed the dinosaurs — and is it coming back?" The rock set in motion a series of scientific inquiries that would ultimately suggest that, like clockwork, Earth might experience a catastrophic housecleaning.

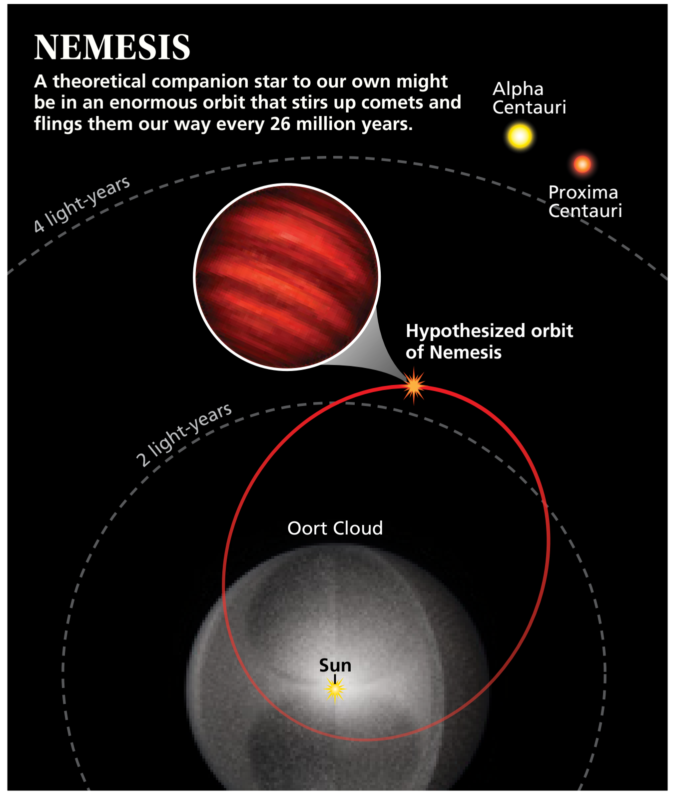
But how? Why? And really? Although the rock set off a course of events that led to the idea of cyclical mass extinctions, the concept would evolve over three decades into a heated debate that continues today.

DOOM OF THE DINOSAURS

Walter and Luis noticed something strange about that rock when they analyzed its chemistry. The element iridium was trapped inside, right in the clay layer where the fossils flickered out — it was a trace, but more than might be expected. While there's plenty of iridium in Earth's core, there's not much in our planet's crust. One way it can land on the surface is to flutter down like ashes when tiny meteorites burn up in the atmosphere. Where did this anomalous amount come from, Luis Alvarez wondered, and what did it have to do with dinosaur death?

"He was always seeking out things that smelled funny and following up on them," says physicist Richard Muller, Luis' colleague at the time at Lawrence Berkeley National Laboratory. "He had identified a mystery." Luis Alvarez had what Muller, writing in *The New York Times Magazine*, called a "killer instinct" for knowing a good problem when he saw one, and he jumped down a rabbit hole of speculation about the rock. Maybe it came from the oceans. Maybe a supernova had irradiated Earth. This kind of brainstorming

FROM LEFT: SCIENCE STOCK PHOTOGRAPHY/SCIENCE SOURCE; LAWRENCE BERKELEY NATIONAL LABORATORY



ROGER RESSMEYER/CORBIS/VCG/GETTY IMAGES

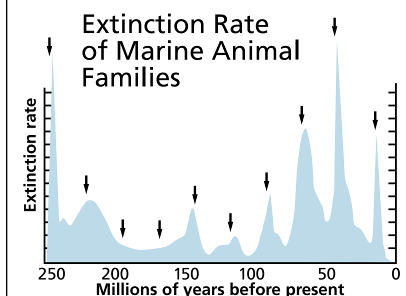
Inspired by his late colleague Luis Alvarez, astronomer and physicist Richard Muller has hunted Nemesis, our sun's theoretical companion star, since the mid-1980s, when this photo was taken.

was Alvarez's scientific *modus operandi*. "One out of 10 ideas might be worth actually trying, and out of these, 1 out of 10 might lead to an important discovery," Muller recalled in *The New York Times* of Alvarez's passed-down wisdom. "You need to have 100 ideas to have a chance at real discovery."

A few years after noticing the iridium, Alvarez came up with his proverbial 100th idea: If a miles-wide asteroid or comet smashed into Earth, it would also throw up a dust cloud that blocked out the sun and snuffed out life. The entry and crash would release iridium from the space rock, and iridium would waft across the globe and settle on Earth's surface, eventually becoming part of the very rock Alvarez held in his hand. This was it, he said: A big rock crashed to Earth, killing not only the dinosaurs but also three-quarters of all species on the planet.

In 1984, Alvarez opened his mailbox to find an envelope from two University of Chicago paleontologists, David Raup and J. John Sepkoski. Inside, their scientific paper suggested that, over the past 250 million years, the death dates of thousands of taxonomic families of marine animals seemed to spike every 26 million years, during one or another of a dozen distinct "extinction events." The scientists believed something beyond Earth was setting the schedule.

Alvarez thought it sounded crazy and prepared a response to Raup and Sepkoski, trying to disprove their idea point by point. When he finished, he showed the letter to Muller and asked him to play devil's advocate. "He always

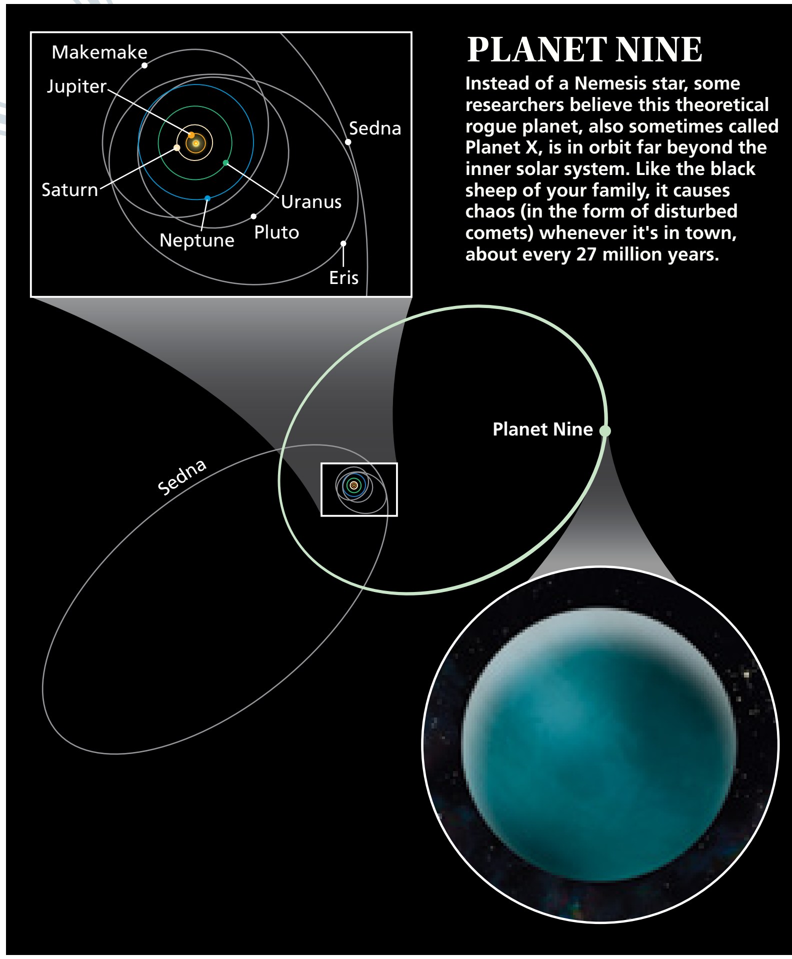


Massive marine animal die-offs seem to spike every 26 million years, according to research that fueled the Nemesis theory.

had close colleagues check over everything he did," Muller says. Soon, in his attempt to prove his colleague wrong, Muller had convinced himself that the paleontologists actually might be on to something, although he wasn't sure what. So he set off to explain what could cause so many species to go extinct every 26,000 millennia.

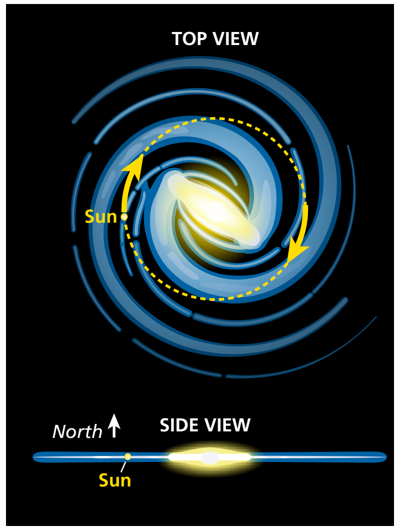
THE HUNT FOR NEMESIS

Muller came to the idea of a secret star in a huge orbit — a 26 million-year-long orbit — with the sun. If it were small and dim, we might never know it was there. But Muller and colleagues realized that, as the star approached the sun, its gravity would tug billions of comets out of their faraway orbits and cast them toward the inner solar system — sometimes, right into Earth. He told Alvarez about the idea. They did a quick calculation to see if such an orbit could exist stably and pull the comets toward Earth. It could. Luis was a believer in math, and so, stunned, he called up the paleontologists to tell them about

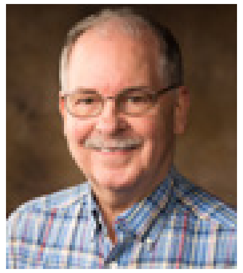


PLANET NINE

Instead of a Nemesis star, some researchers believe this theoretical rogue planet, also sometimes called Planet X, is in orbit far beyond the inner solar system. Like the black sheep of your family, it causes chaos (in the form of disturbed comets) whenever it's in town, about every 27 million years.



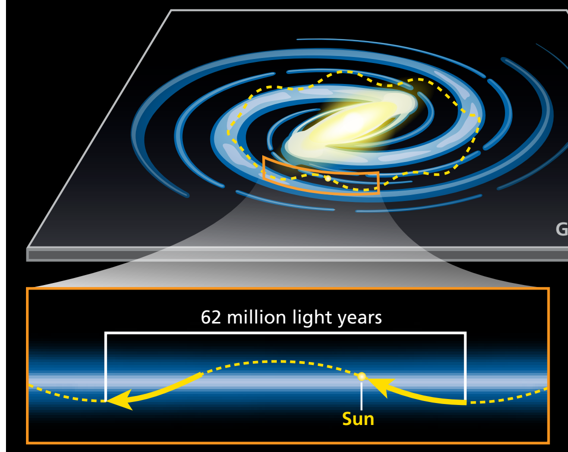
Some researchers look within our solar system for the culprit behind mass extinctions; others suspect it's our solar system's movement around our galaxy, wobbling up and down as we go, that could be hazardous to our health.

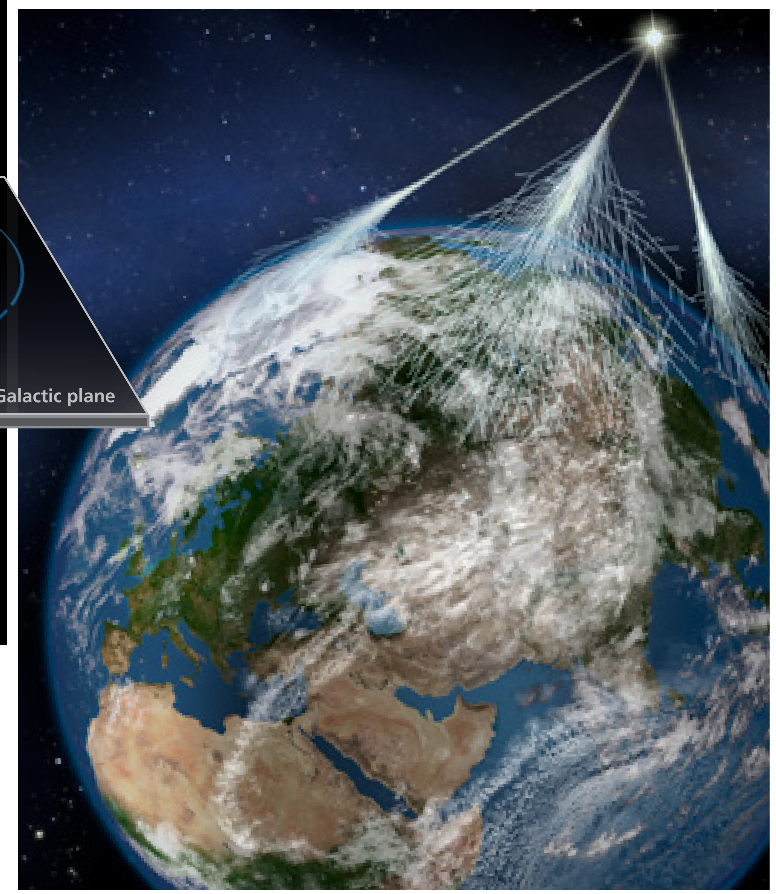


In January, retired astrophysicist Daniel Whitmire published research linking the as-yet-unconfirmed Planet X to cyclical mass extinctions.

COSMIC RAYS

As our solar system travels through the Milky Way, it passes through the galaxy's "north" neighborhood, where cosmic rays are more common, about every 62 million years. That uptick in exposure to the energetic particles could cause a host of problems on Earth, perhaps enough to trigger a mass extinction event.





Adrian Melott (left) and Mikhail Medvedev (right) first proposed the cosmic rays theory in 2007.

the sun's potential partner. The team, at Muller's suggestion, later named it Nemesis.

Luis Alvarez died in 1988, but Muller continues to believe that this "death star" is out there.

As the mass extinction theory gained attention, it also drew out competing ideas about the length of the "cycle of death" and its causes. In 2007, astronomers Mikhail Medvedev and Adrian Melott of the University of Kansas suggested that cosmic rays were behind a 62 million-year cycle of extinction events. Two years ago, astronomers Lisa Randall and Matthew Reece of Harvard University fingered dark matter for a 35 million-year cycle — which they later revised to 32 million years — based on the birth dates of large craters from comet crashes. Most recently, Daniel Whitmire of the University of Arkansas in Fayetteville revived the idea that the potential Planet X (also known as Planet Nine) — a hypothetical Neptune-sized world that Caltech researchers found evidence of in early 2016 — could cause cyclical comet disturbances. Each research team has evidence to support its claim, but none has emerged as a clear winner.

The solar system's shifting environment may change conditions on Earth, making them deadly.

Today, general consensus has shifted. If cyclical extinctions do occur, the current thinking goes, it's the solar system's trip around the galaxy, rather than another star's trip around our solar system, that causes the die-offs. As the sun orbits the Milky Way's center, the solar system drifts in and out of its spiral arms. We also slide up and down, from the galaxy's dense equator to its wispier latitudes. These geographical changes expose the solar system to different forces of gravity and radiation. The solar system's shifting environment may change conditions on Earth, making them deadly.

Melott, for instance, wrote in 2007 that the galaxy's cosmic rays — particles with the energy of a baseball traveling at 90 mph — could be the culprit. He pointed out that more cosmic rays come from the "north" side of the Milky Way. So when the solar system is traveling through that part of the galaxy, about every 62 million years, more cosmic rays hit Earth, causing direct radiation, increased ultraviolet rays and perhaps altered weather patterns.

Melott has also argued against Nemesis as the cause of cyclical extinctions, in 2010 and again in 2013. According to his findings, biodiversity — the variety of life, which would plummet in a mass extinction event — has dipped every 27 million years. The cycle is so precise, he says, that a stealth star couldn't pull it off: The time it would take Nemesis to travel around the sun would change by a few million years each orbit.

MATT REYNOLDS/UNIVERSITY OF ARKANSAS

UNIVERSITY OF KANSAS (2)

DUELING THEORIES

But another scientist, Coryn Bailer-Jones, takes issue with the math behind Melott's models — and, actually, almost everyone else's. Bailer-Jones is a scientist at the Max Planck Institute for Astronomy in Heidelberg, Germany, and a team member of Gaia, a space-based telescope that the European Space Agency launched in late 2013. Gaia is making a 3-D map of the Milky Way by measuring the positions and motions of 1 billion stars.

Measurements from Gaia, which will be released by 2020, will allow scientists to better understand the path our solar system takes through the galaxy and understand its specific galactic surroundings during a given time period. These measurements could reveal that travel through dangerous areas — such as those with more cosmic rays or dense pockets of stars — does show a kind of periodicity that could explain regular extinction events. But Bailer-Jones doesn't think it will.

"I was a little disconcerted to see how apparently strong conclusions can be drawn from rather dubious statistics," he says in a fast British accent. In 2009, he contended that the scientists who favor extinction cycles equate "evidence against randomness" with "evidence in favor of their hypothesis." They tend to test whether their model — for instance, Melott's 27 million-year period — fits the data better than randomly occurring extinctions. If it does, he says, they claim that as evidence supporting a 27 million-year period.

What they do not realize, Bailer-Jones says, is that a third alternative might actually be better than both. A different cycle or multiple interacting cycles could fit just as well. "This is a classic mistake," he says. "They've not actually tested their periodic model."

A few years after Bailer-Jones initially raised the contention, he and Melott went at it directly, rebutting each other point by point in a series of 2013 papers. It got personal at times, such as Bailer-Jones' statement that Melott's work suffers from "either not understanding or not accepting the concept of (evidence-based) model comparison." Bailer-Jones clarifies the conflict, from his perspective, this way: "I think what I'm doing

is right and what they're doing is wrong, and they think the opposite. Unless you can convince them on their grounds that they're wrong, they're not going to budge. But what I'm saying is that it's exactly their *grounds* that are problematic."

Bailer-Jones does not necessarily believe extinctions aren't periodic, but he does think that some scientists oversimplify the situation. "There's no reason these extinctions had to have a common cause. They could be from volcanism, massive impacts, supernovae. It's just complicated." Scientists would do better, Bailer-Jones says, to focus on the more general question of whether extraterrestrial factors influence extinctions than a specific timeline. "It's a shame there's been a hang-up about periodicity," he says.

DEATH AND DARK MATTER

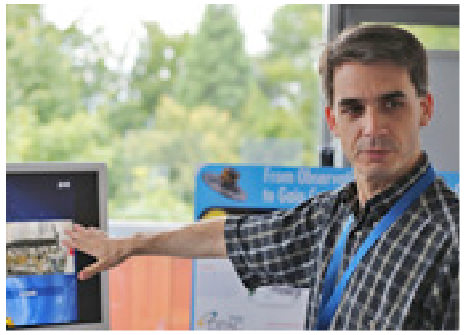
People still are hung up, and measurements from Bailer-Jones' Gaia may, in fact, bolster or bash a new periodicity idea from Harvard theoretical physicist Lisa Randall and her colleague Matthew Reece. Comet crashes, they claim, may well follow a pattern. And what sends them toward Earth is a kind of dark matter, that invisible substance that makes up some 85 percent of the mass in the universe, controlling gravity on the largest scale.

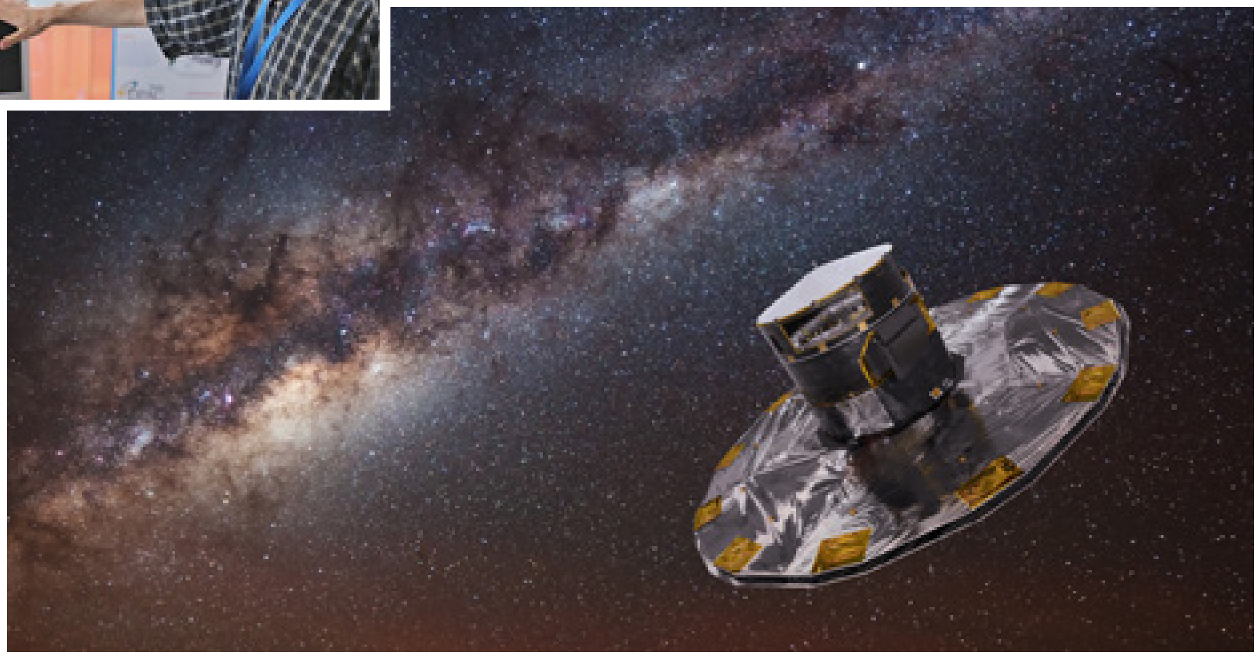
Randall, who explained her theory for a general audience in her 2015 book *Dark Matter and the Dinosaurs*, has proposed that a new form of dark matter coexists with "regular" dark matter. Unlike the normal variety of the stuff, which is fairly inert, this novel type of dark matter loses energy over time and settles into a thin disk in the midplane of our galaxy. That extra matter wields additional gravitational force on everything around it — including comets, sending them out of their distant orbits and into the inner solar system.

In Randall and Reece's model of this dark matter disk, they found that Earth travels through the disk on a regular schedule, oscillating above and below the galaxy's equator while orbiting the galactic center. The changing gravity could be substantial enough to perturb our comets. They used their model of the galaxy to calculate what the cycle's time period would be, and then determined whether that period matched up with the ages of craters from ancient comet impacts. Their dark matter model revealed that a 32 million-year cycle was three times as likely as random cratering.

They've encountered some skepticism, including those who say the dark matter disk is simply a non-possibility. But time will tell, because Randall's idea is testable: Future observations of our galaxy, as well as of tiny galaxies surrounding the

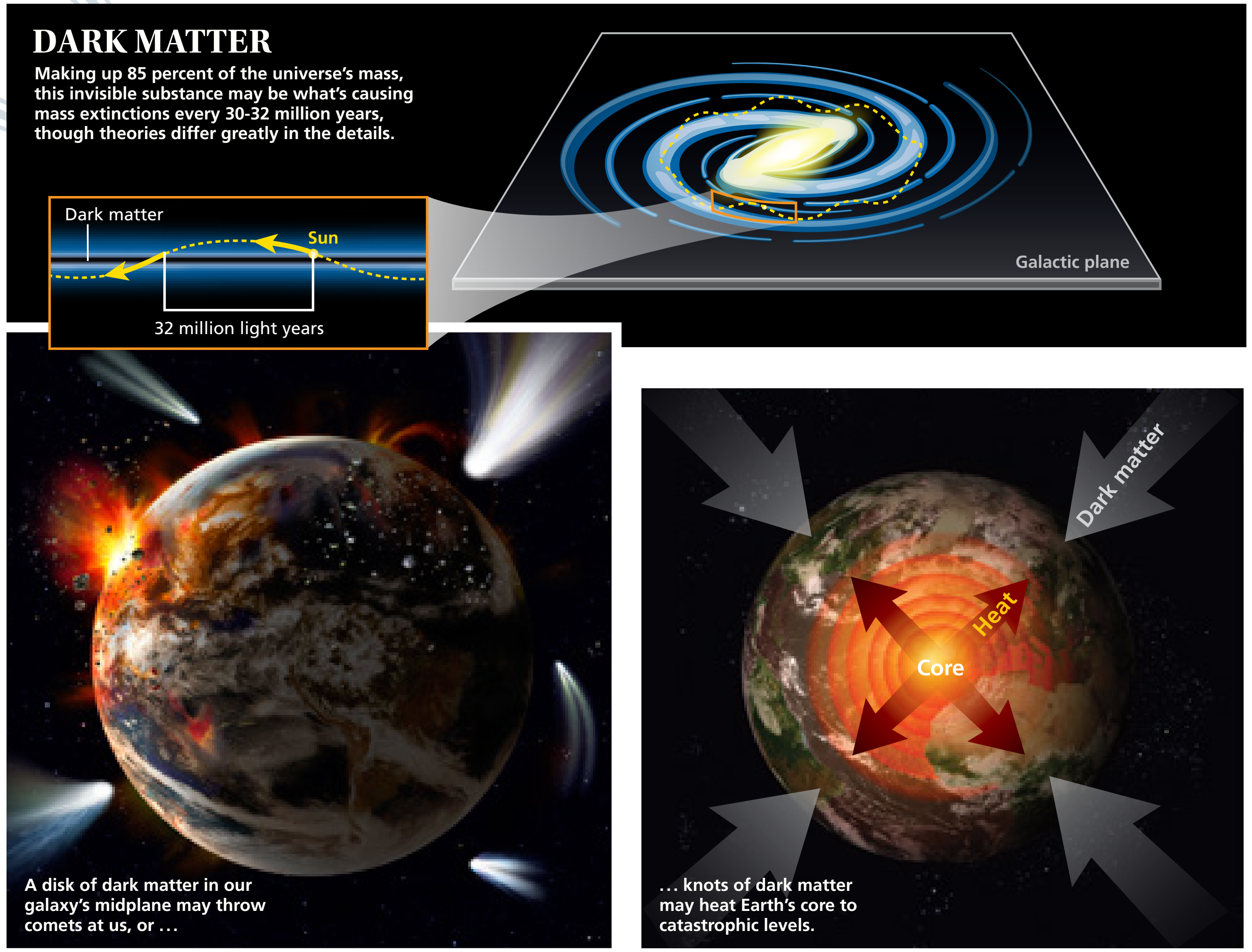
Things outside our atmosphere have written some of our history for us. They will write some of the future, too.





Coryn Bailer-Jones (left), a member of the team behind the space-based European telescope Gaia (below), believes biased methodology may be muddling the question of whether extinctions are cyclic. Data from Gaia, released in the next few years, could clarify the issue.

FROM LEFT: MAX PLANCK INSTITUTE FOR ASTRONOMY; ESA/ATG MEDIALAB/ESO/S. BRUNIER

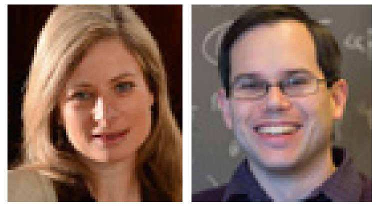


A disk of dark matter in our galaxy's midplane may throw comets at us, or …

… knots of dark matter may heat Earth's core to catastrophic levels.

nearby Andromeda Galaxy, could find this type of dark matter and illuminate the solar system's route through it.

In 2015, Michael Rampino of New York University proposed a different theory about dark matter and mass extinctions. When Earth passes through the Milky Way's disk, as it does every 30 million years, it encounters denser knots of "normal" dark matter. Those invisible particles could tunnel, like cosmic rays, to the center of our planet. There, Rampino says, they would annihilate each other, and that reaction would heat Earth's core — potentially by hundreds of degrees. That fever would, in turn, induce other symptoms: volcanic eruptions, rising seas and changes in climate.



Lisa Randall and Matthew Reece believe dark matter may cause mass extinctions.

While the scientists in this field still differ over the timespan of periodic extinctions and the culprit behind them, all of their competing ideas point back to Raup and Sepkoski's original conclusion: "extraterrestrial causes." After all, we know sometimes stars *do* fling comets at us. We know dark matter *does* exist. Enough cosmic rays can change the environment and climate. We are speeding through the galaxy, sometimes uncomfortably close to other stars.

Things outside our atmosphere have written some of our history for us. They will write some of the future, too. Scientists may have different ideas of what that future will be, and whether it has anything to do with cycles in the millions of years. But they all agree on one thing: "What we're really interested in is where we came from and why we're here," Muller says. "I think the human spirit wants to know how we fit into the world, and where we fit in the universe."

That universe cooked Earth up from the leftovers of dead stars. It nurtures life and then stamps it out. *Qué será será*, and at some point — whether a predictable number of years from now or not — *qué será* won't be pretty. Something is coming for us. Something has already come for 99 percent of the species that have ever lived. We're just the first to notice ahead of time. D

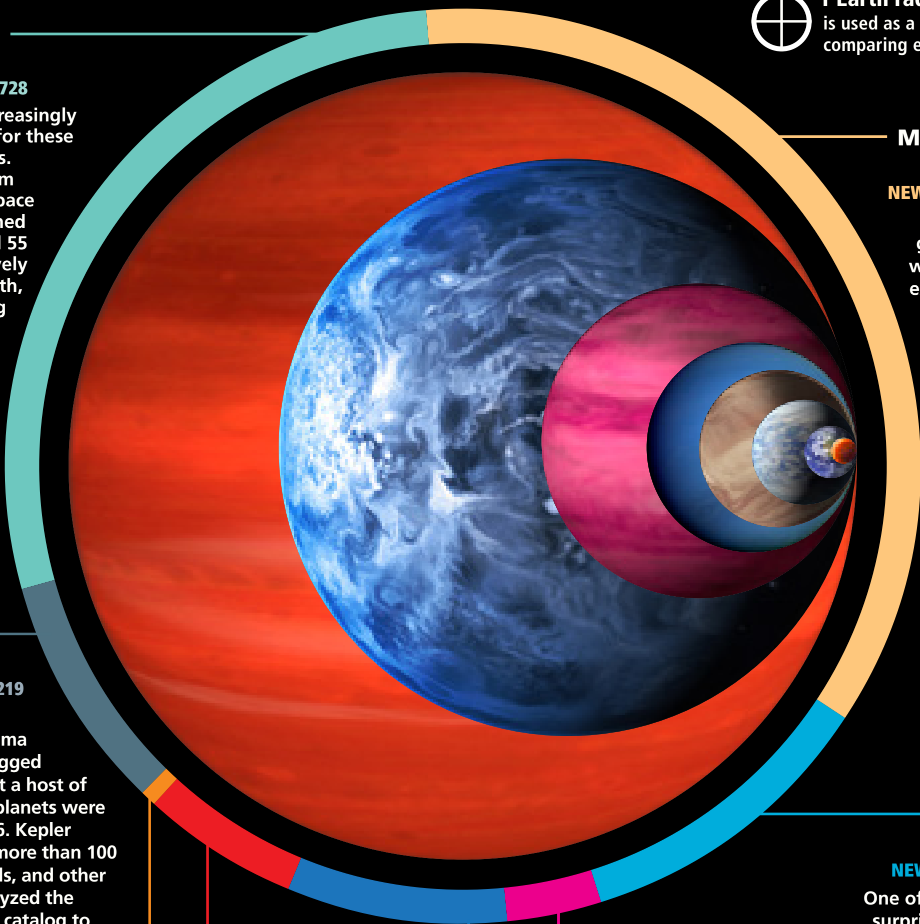
***Sarah Scoles** is a science writer in Denver. She enjoys trails, caffeine and books.*

ESSDRAS M. SUAREZ/BOSTON GLOBE/GETTY IMAGES; PAUL HOROWITZ

PLANETS OF THE MILKY WAY

A NEW LOOK AT DATA from NASA's Kepler space telescope added 1,284 worlds to the exoplanet zoo in 2016, bringing the instrument's total confirmed number to 2,591. Those planets range from the tiny to true behemoths, but most exciting is that more Earth-sized and other smallish worlds are emerging, providing new hope for life in the cosmos. — ERIC BETZ

1 Earth radius (R_E) is used as a baseline when comparing exoplanet sizes



SUPER-EARTH
(1.2 to 1.9 R_E)
NEW: 409 TOTAL: 728
"Earth" looks increasingly like a misnomer for these behemoth worlds. Observations from NASA's Spitzer Space Telescope published in March showed 55 Cancri e, a relatively nearby super-Earth, likely has flowing lava on its permanently sun-facing side, along with temperatures 2,000 degrees Fahrenheit hotter than the night side.

EARTH
(0.7 to 1.2 R_E)
NEW: 130 TOTAL: 219
Our nearest neighbor — Proxima Centauri b — snagged the headlines, but a host of new Earth-sized planets were confirmed in 2016. Kepler scientists added more than 100 likely rocky worlds, and other astronomers analyzed the telescope's entire catalog to find some 200 of all types of planets that might have liquid surface water. "Life is probably a natural consequence of planet formation where water is prevalent," says study author Stephen Kane. "This is a theory that must be tested, however." He hopes these targets can help with that. Meanwhile, Belgian astronomers added three Earth-sized planets in one blow. All orbit startlingly close to the same star, TRAPPIST-1, an ultracool dwarf barely bigger than Jupiter.

SUPER-JUPITER
(13.7 to 22 R_E)
NEW: 11 TOTAL: 142

MARS
(0.5 to 0.7 R_E)
NEW: 9 TOTAL: 17
Technology isn't advanced enough to reveal many tiny exoplanets, but discovering even a handful suggests that many more are lurking unseen.

JUPITER
(8.3 to 13.7 R_E)
NEW: 39 TOTAL: 203

MINI-JUPITER
(5.1 to 8.3 R_E)
NEW: 43 TOTAL: 86

MINI-NEPTUNE
(1.9 to 3.1 R_E)
NEW: 504 TOTAL: 917
These balls of gas, ice, rock and water marked the exoplanet roster's biggest addition in 2016. Not counted in these newcomers is the solar system's own potential Planet Nine, which some astronomers suspect is a mini-Neptune, but has only been theoretically predicted.

NEPTUNE
(3.1 to 5.1 R_E)
NEW: 139 TOTAL: 279
One of Kepler's biggest surprises has been the abundance of Neptune-sized planets across our galaxy. And yet these ice giants remain shrouded in mystery. How did they form? What are they made of? Humanity saw Neptune and Uranus just once, briefly, during Voyager 2's 1989 flyby. In 2016, a NASA-funded team pushed forward with designs for a dedicated mission to Neptune and/or Uranus to better understand all ice giants.

ALISON MACKEY/DISCOVER. PLANETS LARGE TO SMALL: NASA/GSFC/S. WIESSINGER; NASA/ESA/M. KORNMESSER; NASA/GSFC/S. WIESSINGER; NASA/JPL; NASA/ESA/A. FEILD/G. BACON (STSCI); NASA AMES/JPL-CALTECH/T. PYLE; NASA AMES/JPL-CALTECH; SETI INSTITUTE/DANIELLE FUTSELAAR